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Human Systems Integration and Automation Issues in Small Unmanned Aerial Vehicles

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LIST OF ACRONYMS

AUVSI	Association for Unmanned Vehicle Systems International
AVO	Air Vehicle Operator
CIRPAS	Center for Interdisciplinary Remotely Piloted Aircraft Studies
DARPA	Defense Advance Research Project Agency
DERA	Defence Evaluation Research Agency
DoD	Department of Defense
EO/IR	Electro Optic/ Infra Red
FOV	Field of View
GPS	Global Positioning System
GCS	Ground Control Station
HALE	High Altitude Long Endurance
HMD	Head-Mounted Display
HSIAC	Human-Systems Information Analysis Center
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HRI	Human-Robot Interface
HSI	Human Systems Integration
ISR	Intelligence, Surveillance, Reconnaissance
JPA	Job Performance Aid
MAS	Multi Agent Systems
MICA	Mixed Initiative Control of Automa-teams
MPO	Mission Payload Operator
MTBF	Mean Time Between Failures
NATO	North Atlantic Treaty Organization
ONR	Office of Naval Research
PDA	Personal Digital Assistant
PTZ	Pan, Tilt, Zoom
SA	Situational Awareness
SI	Swarm Intelligence
SUAV	Small Unmanned Aerial Vehicle
UAV	Unmanned Aerial Vehicle
UCLA	University of California Los Angeles
UV	Unmanned Vehicles

INTRODUCTION

Unmanned Aerial Vehicle Definitions and History

A Department of Defense (DoD) Website

(<http://www.defense.gov/specials/uav2002/uavpage01.html>) defined Unmanned Aerial Vehicles (UAVs) as “powered aerial vehicles sustained in flight by aerodynamic lift over most of their flight path and guided without an onboard crew.” A Human Systems Integration (HSI) perspective of UAV design and operations is advocated in this report as the best approach to improve UAV effectiveness and to develop future semiautomated UAV systems.

Research and development of UAVs has been ongoing for at least 50 years (Gossett, 2004) and some sources claim that the U.S. military has been involved with UAVs since 1917 (DoD, 2002). Operational UAV systems have proliferated in the past decade, leading to the common perception that UAVs are “new technology.” Approximately 200 types of UAVs are currently in the U.S. military inventory and the number may rise to 500 over the next five years (Garamone, 2002). They range from micro-UAVs (spanning six to nine inches) to High-Altitude Long-Endurance (HALE) UAVs such as the Global Hawk, which is approximately the same size as a fighter aircraft, operates at altitudes of approximately 60,000 feet, and has an endurance of nearly two days.

UAVs can provide the following benefits in DoD applications:

- Eliminate the risk to ground troops and aircrew who would otherwise be performing the mission;
- Enhance aerodynamic performance over manned flight due to lighter weight and freedom from human G-tolerance constraints; and
- Reduce cost.

The U.S. military is committed to rapid development and deployment of unmanned systems as evidenced by the following goals stated by the Senate Armed Services Committee:

It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that:

- (1) by 2010, one third of the operational deep strike aircraft of the Armed Forces are unmanned; and
- (2) by 2015, one third of the operational ground combat vehicles of the Armed Forces are unmanned (Senate Armed Services Committee, 2000).

An overview of UAV military operations and development challenges can be found in the document, “DoD UAV Roadmap 2002” (http://www.acq.osd.mil/usd/uav_roadmap.pdf).

There has been controversy about the basis for classifying or categorizing UAVs. Some of the suggested criteria are airframe size, mission, support requirements, and cost.

Airframe size is the most commonly used criterion. Small UAVs (SUAVs) are not distinguished by unique function, mission relevance, or because they are less expensive. The relevance of SUAVs is based on the operational impact of their logistics—they offer greater flexibility in operational employment compared to larger, more complex UAV systems (DoD, 2002). The definition of “Small UAV” given in the DoD UAV Roadmap 2002 is:

- a. For UAVs designed to be employed by themselves – any UAV system where all system components (i.e., air vehicles, ground control/user interface element, and communication equipment) are fully transportable by foot-mobile troops
- b. For UAVs designed to be employed from larger aircraft (manned or unmanned) – any UAV system where the air vehicle can be loaded on the larger aircraft without the use of mechanical loaders (i.e., two-man lift, etc.)

The U.S. Army, Navy, Marine Corps, and Special Operations Forces have invested in the development of SUAVs to provide tactical imagery to small units (battalion and below) for reconnaissance, surveillance, target acquisition (RSTA), and battle damage assessment (BDA). Two U.S. Army UAV programs, the Hunter and the Shadow, have been deployed successfully in the Persian Gulf, Bosnia, Afghanistan, Iraq, and other conflict locations (DoD, 2002).

The Army’s Future Combat System (FCS) initiative identifies a requirement for two classes of SUAVs:

- Class I = Backpackable; and
- Class II = Vehicle/Man Transportable.

In 2003, the Army Strategic Planning Board designated the SUAV as an “Urgent Wartime Requirement.” The Board projected that SUAVs will be used in direct support of the Global War on Terrorism with immediate application to Army forces engaged in Operation Iraqi Freedom and Operation Enduring Freedom.

UAV research, development, and acquisition programs in the DoD have been sporadic and haphazard over the years and, perhaps as a consequence, the current technologies suffer from high loss rates and require substantial manpower to operate and maintain. One analysis concluded that the U.S. has had a “three-decade-long history of poor outcomes in unmanned aerial vehicle development efforts” (Leonard and Drezner, 2002). However, the U.S. is entering a new era in which the unbridled engineering innovation that has characterized UAV design and development, is likely to give way to more systematic, systems engineering approaches.

Report Objectives

The goal of this report is to identify HSI and automation issues that contribute to improved effectiveness, efficiency, and risk management in the operation of U.S. military SUAVs. To that end, the following three objectives were defined:

- 1) Summarize current HSI issues relevant to SUAV operations;
- 2) Identify areas where short-term HSI improvements might yield gains in effectiveness; and
- 3) Identify research, design concepts, and technologies in automation and related disciplines that are applicable to future SUAVs.

SUAVs hold great promise and will evolve into valuable tactical assets. Any issues or problems identified in this report are intended to hasten the improvement cycle.

The present report is based on three primary sources of information:

- 1) Participation in a series of UAV experiments and field trials at Camp Roberts, California, conducted by the Naval Postgraduate School under the direction of Dr. David Netzer;
- 2) Review of the literature in UAVs, semiautonomous systems, robotics, and related areas, with a focus on HSI and evolving technology; and
- 3) Attendance at the Association for Unmanned Vehicle Systems International (AUVSI) 2003 conference and flight demonstrations at Webster Field, Maryland.

SUAV Overview

This paper will focus on U.S. military SUAVs, as opposed to HALE UAVs or Medium Altitude and Endurance (MAE) UAVs, such as the Global Hawk or the Predator. High altitude generally refers to above 50,000 feet and long endurance to 24 hours or more. By contrast, current SUAVs tend to operate at less than 5,000 feet and their endurance is on the order of several hours. Examples of current SUAVs are the TERN, Silver Fox, Swift, Pointer, Raven, and Dragon Eye. The Hunter and the Shadow, by contrast, are larger and usually are called “Tactical” UAVs (TUAVs). In this report, the term SUAV is used routinely, but the content of this report is equally appropriate for both SUAV and TUAV design concepts and operation.

SUAV missions often are described as “what’s over the next hill?” Related questions might be, “where are they?” or “how many are there?” SUAVs enable small, ground-based military units to perform intelligence, surveillance, and reconnaissance (ISR) missions, reducing the risk to mounted or dismounted troops who would otherwise perform the ISR mission. The objective is to extend the “eyes” of the unit over a greater range, more quickly, and with reduced risk to human life. According to the DoD Roadmap (2002), one of the five “historically validated UAV roles is small unit asset for over-the-hill reconnaissance.” SUAVs will be deployable at or near the front lines, at the company or platoon level, and “will provide the commander with what amounts to a pair of flying binoculars” (DoD, 2002).

SUAVs provide electro-optical (EO) or infrared (IR) sensor data leading to the detection, classification, and identification of vehicles, people, and other tactically relevant objects.

From the HSI perspective, it is important to note that SUAVs do not detect, classify, or identify anything—people do. The SUAV provides the video or IR imagery or other data that enables properly trained observers to perform the detection, classification, and identification functions.

UAV System Example

The basic structure of a typical UAV system may be viewed as an aircraft with the crew physically remote from the vehicle. The upside of the remote crew is reduced human risk, the downside is reduced sensory input about the status of the aircraft (e.g., no noise, vibration, vestibular, or proprioceptive input) and reduced visual information regarding terrain, weather, air traffic, and threats.

A typical UAV system has a minimum of two operators, a pilot or Air Vehicle Operator (AVO) and a sensor operator or Mission Payload Operator (MPO). As shown in Figure 1, these operators work in the Ground Control Station (GCS), which typically is installed in a stationary High Mobility Multipurpose Wheeled Vehicle (HMMWV; or “Humvee”).



Figure 1. Ground Control Station.

A schematic diagram of a typical UAV system is given in Figure 2, including a single UAV, a GCS with two operators, and an image analyst, who represents either a unit commander or a “customer” of the UAV payload data.

The links depict communication (T/R = Transmitter; R/V = Receiver) between the corresponding links. For the purposes of this report, the methods used to implement these communications are not critical.

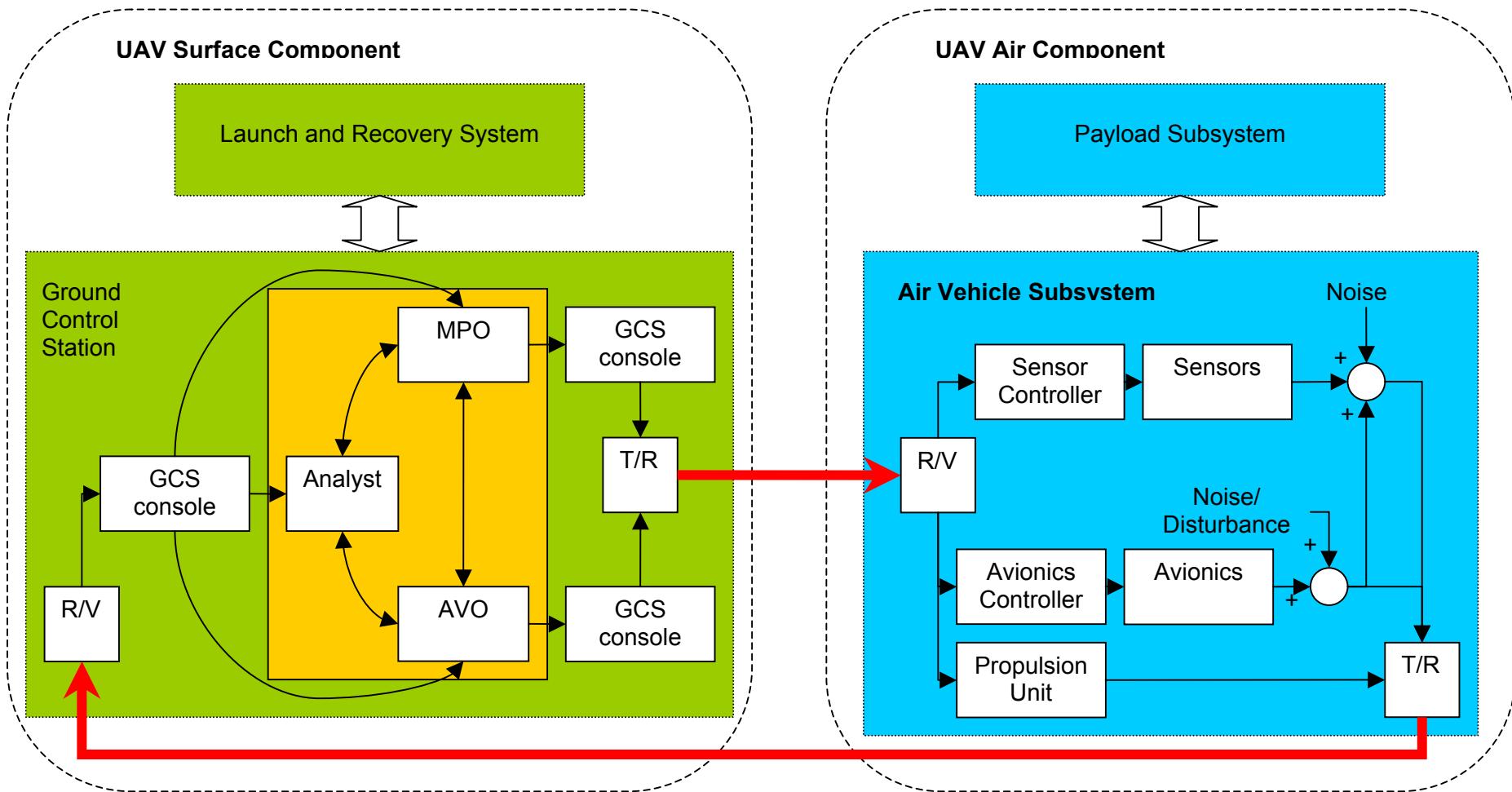


Figure 2. Schematic diagram of a UAV system.

PROBLEM DEFINITION

The current performance of SUAVs has room for improvement, reflecting a technology that is still under development. Some of the challenges that must be faced are that SUAVs:

- are manpower intensive;
- have a large “footprint”;
- need to improve visual data display; and
- have a high loss rate.

Manpower Intensive

Current Army practice is to assign up to 24 people and three UAVs per UAV system. Typically, only one of the three UAVs is airborne at a given time, yielding a “worst case” 24:1 ratio of humans to UAVs. Current UAVs are controlled from the GCS with two operators and often two additional people—an image analyst and a unit leader. Thus, the “Human-to-UAV” ratio could be characterized as 4:1, or 3:1, or, best case, 2:1.

The Defense Advanced Research Project Agency (DARPA) has attempted to push the limits on human control of automata, including UAVs. The objective of the DARPA Mixed-Initiative Control of Automa-teams (MICA) program was to design a system that would enable 30 humans to control 300 entities, or a ratio of 1:10. That would represent somewhere between a 20- to 240-fold improvement over current SUAV manning requirements. This challenge has been called “inverting the control ratio” (Johnson, 2003).

Manpower costs are the largest driver of system life cycle costs. Improving the ratio of humans to UAVs will enable major reductions in the life cycle cost of a UAV system.

SUAV Footprint

The term “footprint” is used to convey both physical and logistical footprint. Future concepts of Small or Micro-UAVs envision air vehicles small enough and light enough to be carried in a backpack, hand-launched, and managed by one person. The current reality is that a manned SUAV system includes the following components:

- GCS, housed and transported in a HMMWV;
- Antennas, generators, and communications gear;
- Remote Video Terminal;
- 24 people;
- 3 UAVs (4 for Hunter); and
- Consumable spares.

The physical and logistical footprint is large and unduly cumbersome to achieve the benefit of one airborne UAV. The challenge is to develop future SUAV systems that are smaller, lighter, more agile, and require less logistic support.

Visual Data Display and Search Effectiveness

Time for Visual Target Detection. Visual search is a demanding, time-consuming task that requires multilayered analysis of human perceptual and cognitive systems (Neisser, 1967). In one target detection experiment (Itti, Gold, and Koch, 2001), the participants were instructed to detect a target in a natural scene photograph; a task similar to UAV search task. The average time required for target detection was 2.8 seconds. When UAV operations lead to a high rate of video flow, the target may not remain visible on the monitor for 2.8 seconds. Operational factors that contribute to this visual search problem are unstabilized imagery, narrow field of view (FOV), low visibility, communication drop outs, and high rate of visual flow (high speed and/or low altitude).

Figure 3 is a representation of the time available to the image analyst to detect a target from the visual scene as a function of altitude and speed. The assumptions underlying the model are:

- The UAV is flying at constant speed over ground (in [km/hour]) and height (in [ft]). Typical air speed for existing SUAVs is in the 80 to 100 km/hr range.
- The camera is stabilized.
- The target is stationary.
- There are no lags, or other errors.
- The FOV (30°) of the camera corresponds to a typical value found in existing SUAVs.

Under these assumptions, the plots in Figure 3 depict the time available for detection by the image analyst. Clearly, low speed and high altitude provide more time for the analyst. If the 2.8-second limit is applied to this theoretical plot, we find that only altitudes above 500 feet are likely to result in target detection.

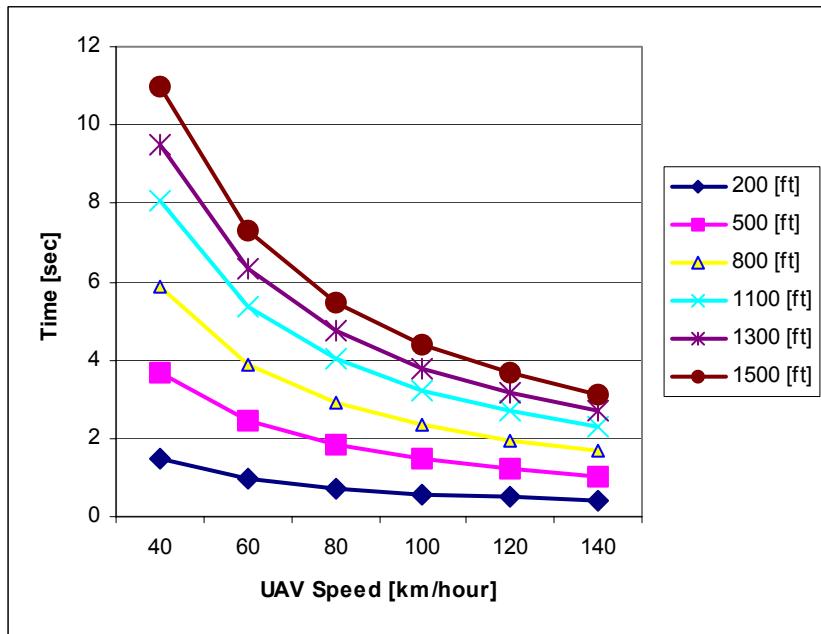


Figure 3. Available time to detect a target.

Visual Data Display Challenges. The demand for “Tactical”-size UAV services in Iraq and Afghanistan indicates that commanders in the field place a high value on the tactical data provided by the TUAVs. However, observation of SUAV operations at Camp Roberts and discussions with operators indicate that improved imagery and image stabilization are needed to improve the ISR capability of SUAVs.

Several issues were observed to influence ISR effectiveness during SUAV search operations at Camp Roberts. The objective of one set of exercises was to detect and classify three types of military ground vehicles in an area approximately 2 x 3 km. The terrain was hilly with clusters of oak trees and occasional dirt roads. Two types of SUAVs were engaged in the search, with a surrogate HALE UAV, the Pelican, operated by the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS). The three Army ground vehicles followed a script for periods of movement followed by either a stop with no concealment or partial concealment under a tree. One of the SUAVs had a fixed “lipstick” type of camera and the other SUAV had a larger, pan/tilt/zoom (PTZ) camera.

Based on our observations, camera type had a large influence on ISR effectiveness. The searches conducted with a fixed camera were unproductive. If the altitude were high enough (approximately 2,000 ft above ground level) to support a reasonable field of view, then the size (retinal angle subtended by the displayed target) and resolution of the target/object images was insufficient to enable detection by the human observer, given the “bounce” of the imagery caused by mild turbulence. If the SUAV altitude were low enough, then the field of view (sweep width) was small, the optical flow rate was high, and the time available for detection was low. The image analyst’s task was difficult at low altitude due to the combination of the high rate of optical flow and the “bounce” of the imagery.

The imagery bounce was considerably more than a small vibration. It was observed to be a magnitude of nearly one video frame, oscillating irregularly at a frequency of approximately 2-4 Hz. For example, if an object were at the top of the monitor image, it would go near, or off, the bottom of the monitor image several times per second. A quantitative analysis of this effect is recommended, leading to recommendations for imagery stabilization.

Searches conducted with a stabilized PTZ camera operated by a MPO were far superior to the fixed-camera system. Imagery from the Navy’s TERN UAV, based on a PTZ camera, but nonoptimal optics, was adequate for the detection task. The surrogate HALE UAV was not used as a primary search sensor, but it provided imagery of extraordinary quality, stability, and resolution.

In the opinion of this observer, the fixed “lipstick” camera was insufficient to support ISR operations. It was extremely difficult to detect a military vehicle parked in the open at a known crossroads and nearly impossible to detect a vehicle partially obscured under a tree. Perhaps this type of SUAV search system could provide useful imagery under constrained conditions, such as very smooth air and open areas with no trees or other concealment. In the Camp Roberts exercises, systems with a shock-mounted, PTZ camera provided far better imagery for the detection task, but that performance comes with a weight penalty. Some research has been done on the development of an intelligent, semiautonomous interface for stabilization of UAV camera images (Korteling and van der Borg, 1997). The relationship between image quality, probability of detection, and the weight penalties that come with a shock-mounted, PTZ camera need to be quantified to support future SUAV design decisions.

One HSI challenge is to define the detection system requirements by working “backwards” from the observer to the sensor. Existing methods for characterizing sensor resolution, like the National Imagery Interpretability Rating Scales (NIIRS) or Johnson criteria (Leachtenaur and Driggers, 2001), need to be extended to characterize the performance of trained human analysts monitoring a streaming video image. This analysis is needed not only for static optical resolution, but for dynamic issues such as optical flow, vibration, and image bounce caused by turbulence and the aerodynamic response of the air vehicle.

Additionally, research is needed to determine the probability of detection for streaming video imagery compared to a series of still images. The frequency and duration of still images are variables that need to be tested. One design option is to allow the operator (image analyst) to select the image iteration rate. Tests are needed to determine whether operator detection performance with unstabilized video imagery is better when viewing a series of static frames. Research on this issue should be done with both static and moving targets. It is possible that static images may be better for stationary targets, while streaming video could have an advantage for detecting moving targets.

Experts in visual perception should analyze the engineering characteristics of UAV video displays to optimize visual performance and pattern recognition. Engineering progress in reducing the size and weight of UAVs will be beneficial only if the video product is

useful, i.e., stabilized and with sufficient resolution and contrast for the analyst/observer to achieve acceptable detection/classification performance.

UAV Loss Rate

The loss rate for UAVs is several times that for manned aircraft. The reliability and sustainability of UAVs establishes the basis for their affordability and their mission availability (DoD, 2002). Accurate data on UAV reliability are difficult to obtain and that seems particularly true for SUAVs. There is no standardized database for UAV mishap reporting and there are a large number of UAV systems developed by a large number of manufacturers and operated by different branches of the military. A definition of UAV reliability comprising four metrics has been proposed (DoD, 2002):

- 1) **Mishap Rate** is the number of accidents occurring per 100,000 flight hours.
- 2) **Mean Time Between Failure (MTBF)** is the ratio of hours flown to the number of maintenance-related cancellations encountered (expressed in hours).
- 3) **Availability** is the number of times a given aircraft type is able to perform its missions compared to the number of times it is tasked to do so, expressed as a percentage (describes the performance of a system while on standby).
- 4) **Reliability** is 100 minus the percentage of times a launched mission is either canceled before takeoff or aborted during flight due to maintenance issues, expressed as a percentage (describes the performance of a system while in operation).

Table 1. Four UAV Reliability Metrics (derived from DoD, 2002).

System	Mishap Rate* per 100,000 hrs.	MTBF (hrs.)	Availability	Reliability
Predator	32	44	67%	82%
Pioneer	334	14	76%	86%
Hunter	55	11	98%	82%

*Class A mishaps, resulting in the loss of the aircraft, a death, or more than \$1,000,000 in damage; for two model series (RQ-1A & -1B; RQ-2A & -2B; RQ-5 pre-/post-1996).

No data were reported for small UAVs, given that the Hunter is usually classified as a “Tactical” UAV. The poor MTBF results, however, are consistent with our observations at the Naval Postgraduate School experiments at Camp Roberts, where four different types of UAVs were flown on multiple sorties on multiple days. While no official record

of UAV losses is available, it was clear that mishaps were frequent, on the order of one every other day. Based on an estimate of 8-12 flight hours per day, that equates to approximately one mishap per 16-24 flight hours. Discussions with one group of experienced, military SUAV operators at Camp Roberts led to their estimate that, for their type of SUAV, the average airframe life duration is approximately 20 flight hours. This figure is consistent with the MTBF data reported by DoD (2002) in Table 1. It is also consistent with the report that NATO lost 20 to 30 UAVs during the 78-day Kosovo air campaign (Mouloua, Gilson, and Hancock, 2003).

In the series of experiments coordinated by the Naval Postgraduate School at Camp Roberts, the causes and contributing factors of mishaps often were uncertain. In some cases, however, the cause was obvious, such as running out of fuel. Most, if not all, current UAVs have no fuel gauge. The operators estimate the flight duration and recover the UAV according to that schedule. When operational requirements place a high value on a few more minutes on station, the fuel reserve may disappear, especially when high ambient temperature has increased the fuel burn rate. As a side note, the tarmac temperature at Camp Roberts on one day of operations was 146° F, probably similar to the temperatures experienced in Iraq.

Other SUAV losses observed at Camp Roberts were due to delamination of the wing (perhaps from long-term storage in very hot, humid conditions in the southeastern U.S.) or to an infrequent, but irksome, software bug that shuts off the engine.

A preliminary analysis of 48 UAV mishaps was reported by the DoD's Human-Systems Information Analysis Center (HSIAC), based on data from the Air Force and Army Safety Centers (Rogers, Palmer, Chitwood, and Hover, 2004). This analysis included 10 years of data for Class A and Class B mishaps, defined as follows:

Class A Mishap: Damage costs of \$1,000,000 or more and/or destruction of an aircraft, missile or spacecraft and/or fatality or permanent total disability of personnel.

Class B Mishap: Damage costs of between \$200,000 and \$1,000,000 and/or permanent partial disability and/or three or more people hospitalized as inpatients.

Of the 48 mishaps, approximately one-third (15) were attributed to mechanical failure and, according to the judgments of Rodgers et al. (2004), all of the remaining 33 mishaps involved some form of human-systems issues. The criteria for these judgments are unclear and unspecified in the report.

The cost of the 48 mishaps was nearly \$14 million for the Army and \$177 million for the Air Force, with the overall average cost per mishap close to \$4 million. A breakout by UAV type for the 48 mishaps is as follows: Predator 32%, Hunter 19%, Shadow 17%, Global Hawk 8%, others 24%.

These data do not provide insight into SUAV loss rates because they will be less than the “Class B” definition of \$200,000. While cost, fatalities, and injuries are the traditional measures of “loss” for manned aircraft mishaps, and may be appropriate for large UAVs, they may not be the appropriate criteria for SUAVs. SUAV mishaps are not terribly expensive, nor are they fatal, but they compromise ISR effectiveness and add to logistic burdens. When an SUAV is engaged in a reconnaissance mission, search time and coverage are lost if it goes down because it takes time to prepare and launch another SUAV to replace it. During that time, the target or object of the search/tracking mission, such as military vehicles or mobile launchers, may have moved to cover. If SUAV loss rates are high, a given unit may not have sufficient spares to provide SUAV ISR coverage.

The HSIAC preliminary analysis of Rodgers, et al. (2004) suggests that two-thirds of SUAV mishaps involve human systems integration issues. This estimate is consistent with historical estimates of “human error” as a causal or contributing factor, which typically are in the range of 60%-80% of all accidents in ground transportation, aviation, and industry (Perrow, 1999). Given the current human-in-the-loop design of UAV control systems, we have no reason to believe that SUAV operations will be different.

A study of the role of human and organizational factors in Army UAV accidents was reported by Manning, Rash, LeDuc, Koback, and McKeon (2004). The authors identified 56 UAV accidents from the U.S. Army Safety Center’s database during the period FY95-FY03. The Army traditionally identifies three basic causes of accidents—human, materiel, and environmental factors. This report summarizes categories of

human-causal factors such as workload, fatigue, SA, training, crew coordination, and ergonomic design. Human error was found to play a role in approximately one-third (32%) of the reported accidents. Two methods of accident analysis were employed and both identified individual unsafe acts or failures as the most common human-related causal factor in UAV accidents. There are at least two important conclusions from the Manning et al. (2004) analysis:

- 1) human-causal factors play a role in a substantial proportion (one-third) of UAV accidents; and
- 2) the Army's current accident reporting method does not support accurate capture of human error accident data.

A systematic basis for tracking SUAV losses is needed. Accurate data on SUAV mishaps are needed to support analyses of causal and contributing factors so that improvements in reliability can be achieved.

There are two challenges here:

- 1) Improve SUAV reliability (the HSI specialists should focus on the subset of mishaps involving human operators or maintainers); and
- 2) Develop a standardized reporting system and database for UAV reliability (including SUAVs) across all services.

Acquisition methods for some SUAVs seem to have circumvented the traditional requirements for reliability analyses and Government acceptance testing, which may contribute to the mishaps attributable to hardware and software problems.

HSI ISSUES FROM NEAR-TERM AND LONG-TERM PERSPECTIVES

Throughout the history of UAV development there has been little or no attention paid to applying “best practices” of HSI and user-centered design. But, UAV programs have matured to the point that haphazard user interface design is no longer acceptable and should not be allowed to contribute to high mishap rates and reduced system effectiveness.

The following categories of HSI issues apply to UAV operations, both now and in the future:

- Human Roles, Responsibilities and Level of Automation;
- Command and Control; Concept of Operations;
- Manning, Selection, Training, and Fatigue;
- Difficult Operational Environments;
- Procedures and Job Performance Aids; and
- Moving Control Platforms.

How can HSI improve SUAV operations? One way to address this question is to consider two different perspectives: near-term improvements that require no new technologies and longer-term improvements, such as semiautomated systems, that will require time and research and development investment.

Near-Term Perspective

Human Roles, Responsibilities, and Level of Automation

The development of current SUAV systems has focused on the fundamental enabling technologies such as aeronautical design, sensors, and communication links with the air vehicle. The simplest SUAVs are essentially hobbyist model planes with a small camera installed. The human role in this type of system is to manually operate a remotely piloted vehicle or teleoperated system.

Morphew (2003) interviewed a number of TUAV operators (AVOs and MPOs) and found that the most difficult tasks were considered to be:

- Launch and landing;
- Identifying and reacting in emergencies; and
- Maintaining situational awareness (SA).

Technologies are under development to support UAV operators in accomplishing these tasks. Several flight management systems have been developed and are currently in use. For example, Piccolo Plus by Cloud Cap is a “user programmable autopilot for UAVs.” This technology provides basic automation functions such as altitude hold and waypoint following. These automation features reduce the operator workload by taking him/her out of the continuous manual control loop. They also change the role of the human operator from direct control to a hybrid of direct and supervisory control.

Further development is needed to provide a mission management system that comprises premission planning and dynamic replanning during a mission. A mission management system for SUAVs might contain the following features:

- Preprogram, reprogram, and manage the flight profile;
- Automated takeoff and landing;
- Preprogram, reprogram, and manage the sensor payload;
- Decision aiding for emergencies and degraded mode operations; and
- Supplemental displays to support SA.

This type of mission management capability exists in U.S. military systems—no new technology is necessary. Worthwhile objectives of a mission management system are to reduce the mishap rate, shrink the 24-person SUAV unit, and enable simultaneous control of multiple UAVs.

The capability to manage and revise the flight profile and sensor payload is essential because, according to experienced military operators from Fort Huachuca and Patuxent River, the majority of all SUAV missions require revision of the mission plan during the mission. The operator must be afforded the capability to change parameters quickly and easily via an excellent user interface. Reverting to manual control should be an available option, but revising the flight profile should be possible without going manual.

In the future, the role of the human will expand to include control of multiple SUAVs and control from a moving vehicle (ground or air). These capabilities and role changes must be accompanied by changes in the user interfaces, training, and operating procedures. The “integration” of HSI is a central concept in evolving the capability of SUAV systems. A challenge for DoD acquisition is to manage this evolution, rather than to acquire new hardware/software, then subsequently deal with the inevitable problems that accompany post hoc development of operating concepts, procedures, training, and user interface functionality.

Command and Control and Operations

SUAV operators need to know where the sensor is pointing. This capability is not provided in most current SUAVs. The coordinates of the center of the sensor field of view are essential, for example, when an image analyst requests a more thorough investigation of a possible contact. Having Global Positioning System (GPS) data on the location of the air vehicle is not sufficient. The coordinates of the sensor view are necessary. A geographic tactical display is needed to show a historical track of the sensor coverage. This display mode would make gaps in coverage immediately evident to the MPO and image analysts. Ideally, the sensor history track would have a decay function selectable by the operator.

System response time and the temporal aspect of team communications. During search operations at Camp Roberts, time lags were observed between an image analyst communicating “possible contact” and the coordinated response from the AVO and the MPO. This problem was exacerbated when the operators did not have information about the coordinates of the possible contact. The time lags can be characterized as an inside- and outside-loop control system. The AVO and MPO have inside-loop control of the UAV and the sensors. If they are using autopilot features, then they must reacquire manual control and take appropriate action. Time is required for the image analyst to assess the video data, perceive, decide, and communicate the possible contact. Then, time is required for the operators to respond. There are several possible solutions to this problem. The analyst, whether local or remote, could be given a manual, rather than verbal, response option that would signify “possible contact” and capture the relevant coordinates. Another approach is team training. The search team can practice the specific communication and performance necessary to minimize response times.

ISR search pattern analysis and codification in a “search template” tool. SUAV operators currently define a search pattern by manually entering data for a series of waypoints. This process is time consuming, tedious, and may not reflect analyses of alternative search patterns. The field of Operations Research can develop search and detection models that will estimate the probability of detection for various search patterns. A software tool could be provided to SUAV operators that would support optimal search patterns while eliminating the requirement to enter every waypoint. With the appropriate sensor performance data loaded into the software tool, operational variables such as altitude, sensor type and FOV, type of target, type of terrain, temperature, and winds could be included in a “Search Template” software tool. The operator would enter points defining the bounds of the search area, and then use the Search Template tool to define the UAV track that provides optimal coverage.

Operations analysis leading to recommendations for system improvements. Most current SUAV systems were developed and fielded without the benefit of systems engineering and analysis. A thorough analysis of current SUAV operations, procedures, and training is recommended to determine ways to improve SUAV system effectiveness. A composite team of experts in aeronautics, sensors, command and control, communications, software, tactics and human factors/HSI would be ideally suited to accomplish these analyses.

Manning, Selection, Training, and Fatigue

UAVs are not unmanned systems. People operate UAVs and how the people are selected, trained, and scheduled contributes to system effectiveness.

The Manning criteria for SUAV operations should be reviewed periodically as the systems evolve. At the present time, operation in the National Air Space is unlikely for SUAVs and the Army's current 96U MOS appears to be sufficient for Army SUAV operations. As the technology changes and the operational concepts change, both the number of personnel in a unit and the entry qualifications will need to be reevaluated periodically.

An enlightening study would be to determine the probability of detection and the time to detection for the top 20% and the bottom 20% of operator skill and proficiency.

Observation of SUAV operations at Camp Roberts indicated substantial differences in operator skill. The expert operator and team are much more likely to be successful. The challenge is to define the selection criteria and continually update them as the job and the pool of candidates evolve.

Strong training programs produce excellent operators. Our unstructured interviews with operators indicated that the Army has a strong training program for UAV operators at Fort Huachuca. The architecture of UAV systems is conducive to embedded training in GCS design. Mission rehearsal training also is feasible, given that a database of the operating terrain and expected objects of interest are available and the setup tools are provided to establish meaningful scenarios.

Fatigue, sleep, and circadian rhythm have strong effects on human performance (Miller, Nguyen, Sanchez, and Miller, 2003). Watch schedules for UAV operators are particularly important when engaged in day and night, 24-hour missions. Recent data indicates that a human operating on no sleep in a 24-hour period exhibits signal detection performance equivalent to someone with a 0.08 blood alcohol level, the legal limit in most states (Doheny, 2004). Manning decisions should ensure that a sufficient number of qualified and trained personnel is available to man a watch schedule. Pushing a crew to extend work schedules will result in performance decrements, no matter how dedicated and motivated the personnel may be.

Difficult Operational Environments

HSI issues in difficult environments should be analyzed to determine risk areas and to identify potential solutions. Night operations are an important example. Dark adaptation phenomena can be important for display design. The possible use of image intensification or night vision devices by UAV operators should be addressed. Other environmental issues should be reviewed, such as extreme temperatures, precipitation, and poor visibility (sand, dust, fog). Finally, worst-case scenarios must be entertained, such as the requirement to operate in chemical and biological protective gear (MOPP 4). The UAV equipment interfaces, training, and procedures must be capable of supporting effective operations in all environments.

Procedures and Job Performance Aids (JPAs)

System effectiveness will be improved by the development and application of doctrine, standard procedures, teamwork guidelines, and JPAs. Development of these policies, procedures, and job aids requires input from expert analysts working with experienced operators. HSI experts who are knowledgeable in job design, JPAs, and training should be included in this process, along with subject matter experts (SMEs) with relevant SUAV experience.

The Navy has conducted an aggressive trial program in JPA applications wherein every job onboard the USS Preble (DDG-88) was provided with a JPA in the form of a personal digital assistant (PDA). Initial findings were strongly positive, indicating that the JPAs reduced training time and supported job performance improvements (Booz Allen Hamilton, 2002). The same benefits can be enjoyed by the UAV community by deploying JPAs.

Moving Control Platforms

Controlling UAVs from a moving platform presents system design challenges, whether the controller is in the air, on the ground, or aboard ship. Human controllers will be confronted with the requirement to maintain spatial orientation and situational awareness (SA) of the controlled UAV(s), while simultaneously sensing and understanding the dynamics of their own vehicle. For example, De Vries and Jansen (2002) found that display of own-vehicle motion reduced the operators' ability to perceive the direction and flight path of a controlled UAV.

The following key issues should be addressed to evolve the capability to manage one or more unmanned vehicles from a moving vehicle:

- How should spatial information about own-vehicle and controlled vehicle(s) be displayed to the UAV operators?
- Can individual differences in spatial orientation and mental rotation be used as criteria for selecting and assigning UAV operators?
- What types of training and simulation systems are necessary to develop the necessary skills to manage complex multivehicle dynamics?

Dowell, Shively, and Casey (2003) found that a heading tape display is more effective than a compass rose display for supporting UAV operator performance. These findings have practical utility, but in the future, this area of research will need to be extended to determine how a moving operator (in a HMMWV or an AH-64 Apache, for example) can best retain spatial orientation and SA with dynamic displays of multiple vehicle dynamics (Durbin, Havar, Kennedy, and Schiller, 2003).

In addition to the issue of navigation/spatial orientation, moving vehicles present three other HSI challenges:

- 1) motion sickness;
- 2) biodynamic interference with manual control; and
- 3) head-mounted display (HMD) bounce.

Motion sickness occurs in these situations due to a combination of actual motion plus “cybersickness” (McCauley and Sharkey, 1992; Morphew, 2003). The visual cues to motion, perceived by information displayed on the HMD, differs from the motion perceived by the inner ear, setting up a “cue conflict” situation (Reason and Brand, 1975).

Biodynamic interference is simply the feed-through to manual control interfaces from the shock and vibration of rough terrain, transmitted through the vehicle suspension to the operator’s body, arms, and hands. This can be a significant problem, depending on the vehicle, the speed, and the terrain.

HMDs tend to resonate at certain frequencies of vertical axis vibration, which are typical in ground vehicles (Sharkey, McCauley, Schwirzke, Casper, and Hennessy, 1995). As the HMD “bounces” relative to the face and eyes, degraded visual performance will occur.

These HSI challenges in operating UAVs from moving platforms will depend greatly on type of vehicle, the terrain, and vehicle speed. For these reasons, HMDs may not be suitable display devices for UAV controllers, especially in moving control platforms.

LONGER-TERM PERSPECTIVE

Despite decades of research and development on UAVs, this technology is still primitive, with the possible exception of the more advanced and expensive HALE UAVs. Current SUAV technology continues to rely heavily on the human controller acting as a remote controller. Given this legacy design concept, the human controller is not capable of directly controlling multiple UAVs effectively, especially in challenging conditions. Breakthroughs in UAV system capability must come from pushing into new conceptual areas such as intelligent, semiautonomous agents of varying size and capability operating as a team in response to “plays” called by the human supervisory controller.

Automation

Advances in technology are proceeding rapidly in many areas that are relevant to unmanned systems such as robotics, semiautonomous systems, biomimetics, and agent-based systems. A brief overview of selected technology topics is given in Appendix A. The term “autonomy” can be applied to all of these technologies because they contribute to a shift away from the human-in-the-loop control that characterizes SUAV control systems.

Automation is likely to play a large role in future UAV systems, but should not be viewed as a panacea. The introduction of highly automated systems can cause serious difficulties such as mode confusion, “automation surprise,” distrust, complacency, and the “out-of-the-loop” operator performance problem (Endsley and Kiris, 1995; Sarter, Woods, and Billings, 1997; Sheridan, 1992; Weiner, 1988).

“Clumsy automation” is the term used to describe automation that makes easy tasks easier and difficult tasks more difficult (Weiner, 1988). This is the opposite of the intended objective of automation, which is to reduce peak workload (i.e., reduce the difficulty of difficult tasks). Woods (1993) summarized studies on automation design this way: “New technology introduced for putative benefits in fact introduced new demands and complexities into already highly demanding fields of practice.”

Many automation functions could be applied to SUAVs, ranging from improved “autopilot” functions to autonomous, collaborative swarms. The former functions were operational 50 years ago; the latter are not yet operational. But, ignoring the technical

feasibility for the moment, what design strategy should be adopted for the sequential introduction of automation features into a UAV system?

Human-in-the-loop simulation is an excellent tool for addressing HSI issues prior to final design of the technological subsystems. The manned-simulation approach enables the tradeoffs to be evaluated between the technical requirements, including automation features, and the HSI issues such as operator roles, tasking, manning, workload, user interfaces, the probability of operator error, and training requirements.

Allocation of System Functions to Automation or Humans

As automation technology evolves, how much control should humans relinquish? What role should the human operator play in UAV systems? The answers to these questions also may evolve, but these HSI and systems engineering questions need to be answered prior to the application of automation “solutions.”

What functions are good candidates for automation? Frequently, automation is advocated for jobs that are “dirty, dull, or dangerous.” Although this saying has good alliteration, it is neither an exhaustive list nor a valid set of criteria. Systems engineers and HSI specialists have the opportunity to determine in advance the control allocation architecture. A process analogous to triage may be warranted, where:

- 1) certain functions may be reserved for human operators;
- 2) other functions are shared, mixed, or adaptively allocated to the best available resource, either human or automated; and
- 3) some functions may be routinely allocated to the automated subsystems.

Through the use of simulation, the challenge of designing function allocation can be addressed early in system design, prior to engineering or technological determinations about **how** the automation features might be implemented.

Table 2 gives a first approximation of separating top-level (human control), mid-level (overlapped, shared, or adaptive control), and lower-level tasks (prime candidates for automation). The “top-level” list is intended to endure, no matter how sophisticated the technology may become in the future. The mid-level tasks are currently accomplished

by humans, but could be allocated, at least some of the time (adaptively), to intelligent automation in the future. The lower-level tasks also are frequently accomplished by humans, especially during takeoff and landing, but current technology is capable of performing these functions.

Table 2. Example of Function/Task Allocation for SUAV Systems.

Top-Level Human Tasks	Mid-Level Shared Tasks	Lower-Level Automated Tasks
1. Define Mission Objectives	1. Airspace Deconfliction; "See and Avoid"	1. Vehicle Control (autopilot functions)
2. Specify/Assign Team and Assets	2. Terrain Avoidance	2. Counter Environmental Disturbances
3. Specify Location (region, area)	3. Implement Tactics	3. Maintain Sensor Lock-on
4. Specify Time Period	4. Navigate	4. Collision Avoidance Processing
5. Determine Tactics	5. Avoid or Investigate Possible Threats	5. Store or Transmit Data
6. Determine Contingency Plans	6. Teamwork Dynamics	
7. Initiate Operation	7. Sensor/Payload Control	
8. Modify Mission Objectives and Tactics	8. Takeoff and Landing	
9. Launch Weapons		
10. Terminate/Recall Mission		

Sheridan (1992; 2002) has provided excellent insights into automation, supervisory control, and system design. As mentioned earlier, a common error is to automate whatever functions are easy to automate and let the human do the rest. As noted by Sheridan (2002):

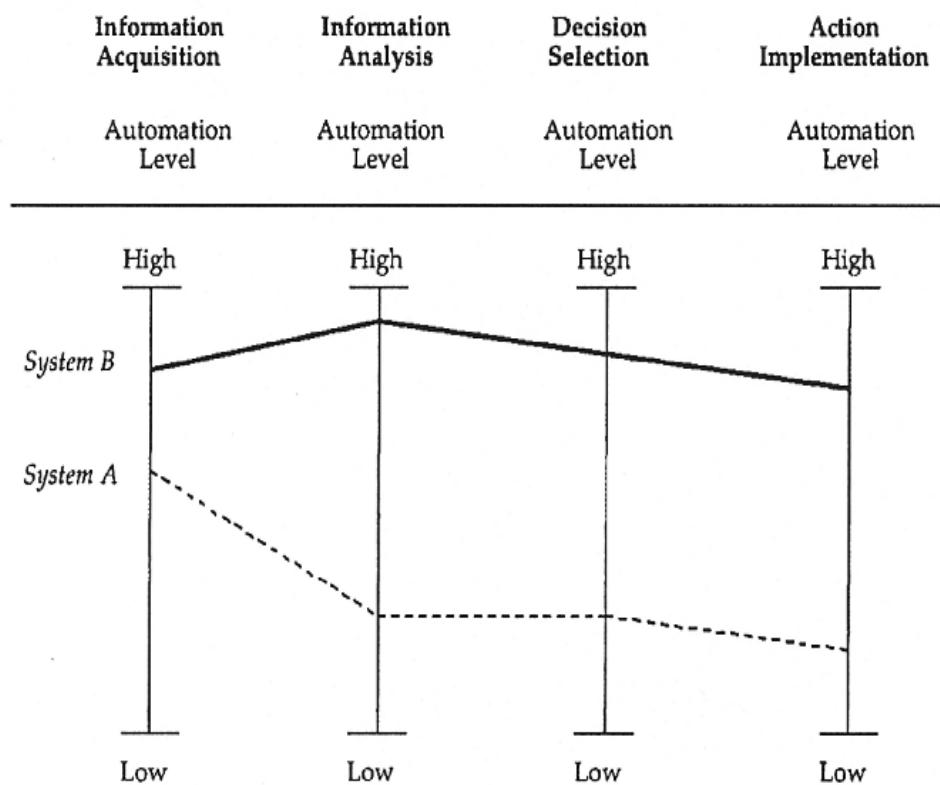
From one perspective this dignifies the human contribution. From another it may lead to a hodgepodge of partial automation, making the remaining human tasks less coherent and more complex than they need be, and resulting in overall degradation of system performance.

Advancements in the human-system engineering processes for developing automation functions in manned military aircraft are relevant to UAV systems (Taylor, Bonner, Dickson, Howells, Miller, Milton, Pleydell-Pearce, Shadbolt, Tennison, and Whitecross, 2002). The authors advocate adaptive automation and decision aiding based on cognitive systems engineering principles. Communication of intent is important because, in a hierarchical tasking system, the intent of the commander flows down

through the task hierarchy. The concepts and methods suggested by Taylor et al. (2002) were integrated in the Cognitive Cockpit (COGPIT) program of the United Kingdom Defence Evaluation Research Agency (DERA). These concepts are applicable not only to aircraft interfaces, but to UAV systems, both for user interface design of the GCA and for automation system design.

One approach to defining types and levels of automation has been suggested by Parasuraman, Sheridan, and Wickens (2000). This model or framework features the selection of a level of automation for each of four stages of human information processing, as shown in Figure 4.

Figure 4. Levels of automation for each of four stages of human information processing (from Parasuraman et al., 2000).



According to this model, four stages of human information processing can be applied both to human information processing and to automated functionality. The design of any specific system can apply automation at a selected level in each of the four stages. In the example given in Figure 4, System A has less automation than System B and has its

highest level of automation in the “Information Acquisition” stage. A medium to high level of automation in this first stage would imply support for sensor management and perhaps some degree of highlighting, preprocessing, or preliminary object detection/recognition aiding.

Parasuraman et al. (2000) emphasize the importance of testing and evaluating preliminary choices of automation functionality. Iterative testing establishes the best automation levels for supporting human operator performance. A secondary testing criterion would be the reliability of the automation functionality. Reliability of automation is important for achieving the trust of the human operator.

There have been several attempts to define stages or levels of automation.

Sheridan (1992) provided a definition of ten levels of automation (see Table 3).

Table 3. Sheridan’s “Scale of Degrees of Automation” (from Sheridan, 1992).

1.	The computer offers no assistance; human must do it all.
2.	The computer offers a complete set of action alternatives, and
3.	Narrows the selection down to a few alternatives, or
4.	Suggests an alternative, and
5.	Executes that suggestion if the human approves, or
6.	Allows the human a restricted time to veto before automatic execution, or
7.	Executes automatically, then informs the human, or
8.	Informs human after execution only if asked, or
9.	Informs human after execution if it, the computer, decides to.
10.	The computer decides everything and acts autonomously, ignoring the human.

Some of the HSI challenges in developing effective automation systems in UAVs are to develop:

- 1) criteria for the application of automation features;
- 2) a consistent and unambiguous way to inform the user about the status of modes and automation features; and
- 3) a design that empowers the human user to reacquire control of any automated variable upon request.

HSI Issues in Automation

Distrust and Complacency. When automation is introduced, the job of human controllers usually is shifted from direct control to supervisory control (Sheridan, 1992; 2002). A common reaction to this shift in roles and responsibilities is for the human controllers to distrust the automation features. This problem is exacerbated when early versions of an automated system are perceived to be unreliable, which can be expected when reliability is less than 95%.

In a recent review of trust in automation, Lee and See (2004) defined trust as “the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability.” After automation has been integrated into ongoing operations the problem of “distrust” is more likely to be replaced by the problem of overtrust or complacency. The users (human operators, supervisory controllers) trust the automated system too much, leading to complacency in their role as “supervisory controller.”

Lee and See (2004) use the terms “appropriate trust” or “calibrated trust” because humans could err in either direction—distrust a reliable automation feature or overtrust an unreliable automation feature. Distrust leads to disuse (the capabilities of automation are rejected), whereas overtrust leads to complacency and misuse (violation of assumptions or inappropriate reliance on automation).

Design and training approaches are suggested by Lee and See (2004) to achieve appropriate trust in automation, including:

- Design for appropriate trust, not greater trust;
- Show the past performance of the automation;
- Show the process and algorithms by revealing sensible intermediate results;
- Show the purpose and design of the automation in a way that relates to the user’s goals; and
- Train operators about the expected reliability and intended use.

Case Example. A case example of overtrust or complacency was observed at Camp Roberts as a UAV was returning to the landing strip under automated control of altitude and heading. Because no direct, manual control was being exercised and no search process was ongoing, the operator(s) were loosely monitoring the video image on a small back-up display. The unscheduled descent was not noticed until it was too late. Upon impact, the video imagery flow became static, leading one operator to exclaim, “I think we may have crashed!” The three other team members met this statement with incredulity, until they observed the static video close-up of the ground. An intermittent software error was thought to have been the likely source of the problem, extending landing gear and cutting power. An alert operator, monitoring the situation closely, may have had time to reacquire manual control prior to impact. Overtrust in the altitude-hold automation feature may have contributed to the failure to detect the unintended descent.

Human Error in Automated Systems. Reduction of human error often is given as a basis for the decision to automate system functions. If the human is removed from the control loop, he cannot make an error. Or can he? Early use of automation in the commercial airline industry provides lessons that can be applied for UAV control. Because a majority of airline crashes were attributed to “human error,” many technologists in the 1970s believed that automation was the best way to reduce human error. Wiener and Curry (1980) analyzed cockpit automation as the “glass cockpit” was introduced into commercial aviation in the 1970s. Their analysis did not support the assumption that automation would decrease human error. Rather, the authors suggested that automation changes the types of errors and, in fact, may create opportunities for new types of human-system errors.

Human error is complex (Reason, 1990). One reason to adopt a systems engineering and HSI perspective on the development of automated systems is to identify in advance various forms of human error and design the system to prevent them or limit their consequences.

Mode Confusion. The introduction of the “glass cockpit” to commercial aviation in the 1970s required a transition period during which flight crews had to learn new controls, displays, new roles (supervisory control), and a proliferation of computer-controlled

automation features. One common problem with the new feature-rich automation systems was mode confusion, sometimes resulting in “automation surprise” (Sarter and Woods, 1995; Sarter, Woods, and Billings, 1997).

This problem of mode confusion and automation surprise occurs for one of two reasons:

- 1) the effect of a specific operator (pilot) input is mode-dependent; or
- 2) the operator is surprised at the behavior of the automated system because he/she made an incorrect assumption (or had an inadequate mental model) about the current mode of operation.

The likelihood of such an error is more apparent when one understands that one type of commercial airline cockpit has 11 auto thrust modes, 17 vertical flight path modes, and 10 lateral flight path modes. This type of feature proliferation and complexity sets the stage for human operators to suffer mode confusion, to enter erroneous data, or otherwise interact with the automated system in a way that does not achieve the intended result.

Mode confusion is not a problem with current UAVs, but will be arriving soon, as more complex automated systems are introduced. If system designers focus on HSI and on applying the “lessons learned” from the introduction of automation in commercial aviation over 20 years ago, the result will be a more graceful introduction of automated features into UAV systems.

Integrating human controllers into automated systems is a critical research goal for UAV systems. The fundamental engineering technologies that enable UAV functionality, such as aeronautical systems, propulsion systems, sensors, and communications links, need continued development. But, in addition to those fundamental engineering technologies, major improvements in SUAV effectiveness and reductions in life cycle cost can be obtained from human-centered design of automation features.

RESEARCH RECOMMENDATIONS

Throughout this report, opportunities for research and development have been suggested directly or implied. The following list is a compilation of research recommendations mentioned in this report, sorted by major categories:

Automation

1. Determine the automation features, selection criteria, and training requirements that would be needed to support the control of multiple SUAVs by a single operator.
2. Perform research on defining the roles, responsibilities, and tasks for human operators as automation technology evolves.
3. Develop UAV mission management (planner/replanner) systems to reduce operator workload.
4. Develop a search-aid software tool to assist UAV operators to select and implement good search tactics for given situations.
5. Perform research on adaptive automation systems, mixed-initiative systems, and collaborative control to determine successful strategies and designs for semiautomated UAV systems.
6. Perform research to establish guidelines for avoiding mode confusion and automation surprise in semiautomated UAV systems.

Manpower, Personnel, and Training

7. Conduct research and analysis on how to improve the ratio of humans to SUAVs without incurring a reduction in system effectiveness.
8. Reduce the manpower requirements of a SUAV unit by implementing HSI design for maintenance and flight operations support.
9. Develop training materials for the instruction and qualification of image analysts, including mission rehearsal capability to detect, classify, and identify objects and entities relevant to upcoming mission.
10. Develop embedded training systems to promote skill acquisition and maintenance using the GCS as the training simulator.
11. Develop personnel selection criteria based on quantitative measures of UAV system performance (e.g., probability of detection; time to detection; probability of false alarm; spatial orientation; vehicle control; sensor control).

Mishaps and Mishap Reporting

12. Develop a standardized, DoD-wide reporting system for UAV mishaps.
13. Reduce SUAV mishap and loss rates by analysis of losses where operator errors are cited as a causal or contributing factor.

HSI and Systems Analysis

14. Execute a thorough HSI and systems engineering analysis of current TUAV and SUAV operations to determine major contributors to success (and failure) of current systems (aeronautics, propulsion, sensors, communications, control systems, user interfaces, tactics, and utilization of data in the larger command and control environment).
15. Ensure contribution of HSI to the ongoing process of the design and development of a common console for UAV control.

Policy and Procedures

16. Prepare for 24/7 operations by developing guidelines for managing sleep and fatigue through chronohygiene and watch-standing procedures.
17. Design and train for difficult environmental conditions—night, poor visibility, and chemical defense gear.

Human Factors Engineering of System or Subsystem Design

18. Define UAV detection hardware and software system requirements by establishing criteria (time, contrast, resolution, visual angle, motion, and other relevant factors) for human detection and identification of mission-relevant objects.
19. Perform research to determine the best practices for using static and dynamic imagery to support human target detection.
20. Develop hardware and software to stabilize the visual imagery.
21. Implement the technology to monitor the coordinates of a camera or other sensor aboard SUAVs.
22. Develop Job Performance Aids (JPAs) and decision aids for UAV operators
23. Develop design guidelines for displays and other system features that will enable UAV operators to perform their tasks in a moving vehicle (air, ground, or surface) while maintaining spatial orientation and situation awareness.

24. Develop simulation capabilities to enable analysis of UAV effectiveness as a function of new technologies, automation, procedures, displays, and other system features.

Research Recommendations from Appendix A

25. Perform research on intelligent agent systems and multiagent systems as a basis for improving SUAV effectiveness while reducing the UAV footprint and operator workload.
26. Perform research on levels of autonomy and semiautonomous systems with application to SUAV systems.
27. Perform research on swarms and stigmergy to determine how to apply them to automation in SUAV systems and micro UAV systems with continued focus on the human operator role as supervisory controller.
28. Determine the interchange and mutually beneficial overlap between Human Systems Integration and Human Robot Interfaces with reference to SUAV applications.
29. Perform research on how hierarchical control architectures like Playbook might be implemented in SUAV systems with one human operator controlling multiple SUAVs.

APPENDIX A: AUTONOMY TECHNOLOGY

This overview is intended to identify some of the research issues that are being addressed in autonomy and related disciplines that are relevant to future UAV design and operations. It is not a comprehensive review of the scientific and technical literature in these fields.

Robotics, Intelligent Agents, and Multiagent Systems

UAV development can be considered a subfield of robotics and, thus, advances in robotics are important to UAV design and performance. Research and development programs in robotics are ongoing at leading universities in the U.S., Europe, and Asia.

Robots (including UAVs) face many of the same challenges that human perceptual systems perform so well, such as visual-inertial stabilization and the analysis of whether you are moving or the environment is moving (Panerai, Metta, and Sandini, 2000). These intersensory processes and feedback loops provide the foundation for exploiting maximum visual acuity (gaze stability) and for discriminating between self-motion and motion of the visual scene. Compensation for motion of either sort is necessary to maintain image stability on the retina (or optic sensors). As mentioned earlier in this report, the lack of this capability has been observed to be a problem for small UAVs without image-stabilization systems. Image stability for some minimal duration is a fundamental requirement in an optical detection system, whether a human analyst or an automated agent is processing the image.

A demonstration of autonomous robotic capability called "The Grand Challenge" was sponsored by the Defense Advanced Research Project Agency (DARPA) in March 2004. The top 15 autonomous ground vehicles participated in a challenge to win a \$1 million prize by navigating 140 miles through the Mojave Desert from Barstow, California to Primm, Nevada. The entrants included teams like Cal Tech, Berkeley, and Carnegie-Mellon using significantly customized vehicles built on the chassis of Chevy Tahoes, HMMWVs, and other off-road vehicles. Not only did none of the robots make it to the destination, only two of the teams made it as far as seven miles. Most of the entries failed to traverse more than a few hundred yards. According to one news item, "it was a pretty humbling display for unmanned robot vehicle technology." The results underline DARPA's prescient selection of the event name, "The Grand

Challenge.” Obviously, overcoming difficult environmental obstacles is truly a grand challenge for autonomous off-road ground systems in 2004.

The results of the 2004 DARPA Grand Challenge indicate that frequent “reality checks” (test and evaluation under operational conditions) are necessary as autonomous technologies are developed and before the lives of U.S. military personnel are dependent on their success.

Intelligent agents have the common requirement that they must be goal directed. An agent must exhibit purposeful behavior and have an explicit representation of their goal (Huber, 1999). Research on multiagent systems (MAS) has commonly led to hierarchies of autonomy with various decision-making procedures employed by the agents. MAS prototypes have demonstrated capability in simulated adversarial games such as robot soccer. Stone (1998) applied machine learning techniques to MAS and demonstrated that a group of independent agents can work towards a common goal in a complex, real-time, noisy, collaborative, and adversarial environment.

Research in Sweden has developed an approach for directing a hierarchy of intelligent agents in real time. Their approach was to enable control of UAVs by allowing the human controller to access an agent at any level of abstraction, as needed. The human can acquire control over an agent in a hierarchy, but the agent will be expected to continue with other tasks as well as fulfilling the operator’s request (Scerri, Reed, and Torne, 1999). This architecture avoids the common problem of agents abandoning tasks when interrupted by the human operator. Agents at lower levels of the hierarchy negotiate among themselves to decide which will be responsible for a task given by either the human operator or a higher-level agent. As in a human organization, guidance and requirements can be issued at varying levels of abstraction and carry different weights.

In Australia, researchers have developed autonomous mobile robots with local intelligence. The robots do not rely on a Global Positioning System (GPS), but use on-board “vision” sensors to perform tasks such as navigation, map generation, and coordinated group behavior (Petitt and Braunal, 2003). The authors attribute the success

of this research program to the use of a “behavior-based” approach to controlling the mobile robot agents, rather than the traditional control algorithm approach.

Under the DARPA Mixed-Initiative Control of Automa-teams program (MICA) one group of researchers applied the “Playbook” concept to enable a single human operator to supervise a team of six robots in RoboFlag, a simulation of the child’s game “capture the flag” (Parasuraman, Galster, and Miller, 2003). Emulating a child’s game may seem trivial until one appreciates that success requires teamwork, perception of the location of the high-value target, and tactics for countering opposition offense and defense. These capabilities are not unlike a UAV ISR mission.

Johnson (2003) described the DARPA MICA program as having two approaches to one goal—the control of large-scale teams of semiautonomous vehicles by a relatively small number of human operators. The two approaches are:

- 1) autonomous control theoretic techniques; and
- 2) mixed-initiative techniques for integrating humans into the control process.

The first approach is based on a hierarchical command and control structure including:

- Team composition and tasking;
- Team dynamics and tactics; and
- Cooperative path planning.

The second approach focuses on how to design the system around the potential behavior of the human operators:

- Meaningful cooperation between human decision makers and teams of semiautonomous entities; and
- How is the performance and stability of the system affected when an operator can take control at varying levels and times?

Johnson (2003) makes the important point that “it is rare historically for an R&D program to explicitly consider human interaction issues simultaneously with technology

development.” The DARPA MICA program objectives established a requirement for robotics and control engineers to work collaboratively with cognitive engineers and HSI experts to achieve a human-centered design perspective.

The MICA program was discontinued after approximately two years into the four-year plan. According to the coordinator of the MICA program, the progress was apparent during the first two years, but it also became clear that both the Unmanned Combat Armed Rotorcraft (UCAR) and Joint Unmanned Combat Air Systems (J-UCAS) programs would have to pursue developments similar to MICA in multi-UAV control. DARPA concluded that further development of this technical topic should be continued within the scope of those larger and pragmatically focused programs (Kott, 2004).

Autonomy

A key issue for the design and implementation of future UAVs is “levels of autonomy,” which can, theoretically, range from teleoperation to fully autonomous systems. Yavanai (2003) defined autonomy as,

an attribute of a system which characterizes its capability to accomplish the system’s assigned mission goals without any, or with only minimal, abstract level intervention of an external cooperative entity, i.e., a remote agent or a remote operator, while the system is operating under constraints and under unstructured, unexpected, and dynamic uncertain environment as well as under evolving dynamic uncertain scenario conditions.

Neidhoefer and Krishnakumar (2001) developed an intelligent aircraft control architecture based on “levels of intelligent control.” They adopted concepts from computational intelligence such as neural networks, genetic algorithms, and adaptive critics.

Robotics research programs have wrestled with ways to enable multiple levels of autonomy. Studies at the Johnson Space Flight Center have identified the need for adjustable autonomy (AA) because humans sometimes need to be involved, not only at the highest (decision/deliberative) level, but all the way down to teleoperation of systems that were intended to be fully autonomous (Bonasso, 1999). Their experience in developing space applications led to the following recommendation: design the control

architecture for full autonomy; then relax the autonomy restriction at each level, beginning with the highest.

The Canadian Defence Research and Development group compiled a technology summary of autonomous collaborative unmanned vehicles (Bowen and MacKenzie, 2003). The report concludes that autonomous control is the key to achieving maximum UAV utility. This conclusion extends to Unmanned Vehicles (UV) of all kinds—space, air, ground, water surface, undersea, and other types of vehicles. Gaps in knowledge were identified in the following technology streams: Robotics, Mobility, and Navigation.

Another approach is to consider an intelligent robot to be capable of acting as a peer of the human operator, worthy of exhibiting collaborative control (Fong, Thorpe, and Baur, 2001). This type of relationship between the human and the robot also is called a “mixed-initiative” architecture.

One objective is to develop a control architecture that will allow a single human operator to interact with multiple robots, while maintaining reasonable workload and effectiveness (Goodrich, Olsen, Crandall, and Palmer, 2001). This objective can be extended to allow multiple human users to manage multiple robots, perhaps of different types, from multiple control platforms, some of which may be mobile.

Swarms and Stigmergy

Several concepts merge under the heading of “swarms” including biomimetics, stigmergy, self-organizing systems, and emergent behavior. These concepts are worthy of analysis for their potential application to UAV design and operations. “Biomimetics” is the term given to biologically inspired technology (Bar-Cohen and Breazeal, 2003). Biomimetic programs seek to simulate or mimic the mobility, intelligent operation, and functionality of biological creatures.

One aspect of biomimetics is the analysis of swarming behavior, which is common in nature (e.g., bees, wasps, and ants). Similarly, flocks of birds and schools of fish exhibit closely coordinated group behaviors (Clough, 2003).

According to a NASA/JPL Website [<http://dsp.jpl.nasa.gov/members/payman/swarm/>],

Swarm Intelligence (SI) is the property of a system whereby the collective behaviors of (unsophisticated) agents interacting locally with their environment cause coherent functional global patterns to emerge. SI provides a basis by which it is possible to explore collective (or distributed) problem solving without centralized control or the provision of a global model.

The rise of agent-based simulation systems is in concert with swarming biomimetics.

Hoffmeyer (1994) defined a swarm as, “a set of mobile agents which are liable to communicate with each other directly or indirectly and which collectively carry out a distributed problem solving.” An individual insect has extremely limited intelligence, yet, by following simple rules, the emergent behavior of the swarm efficiently gathers food, transports/retrieves heavy prey, and defends itself.

Stigmergy is the use of the environment to communicate. Bonabeau and Theraulaz, (2000) discuss how ants leave a trail of pheromones, a form of stigmergy, to forage efficiently. For example, an ant leaves a pheromone trail outbound and, after finding food, doubles the intensity of the pheromone trail when inbound. Subsequent ants will tend to follow the strongest trail. These same rules—the pheromone serves as an attractor sign, but has a decay function—can be used computationally to solve difficult problems such as the “traveling salesman.” In this problem, a person must find the shortest route by which to visit a given number of cities, each only once. This classic problem is “devilishly difficult” using traditional computational methods because for just 15 cities, there are billions of route possibilities (Bonabeau and Theraulaz, 2000). For UAV applications, an analogous type of communication among the “swarm” could provide information about what areas of a search region have been recently covered.

“Digital pheromones” have been suggested by Parunak, Purcell, and O’Connell (2002) as an effective way to coordinate swarming UAVs. They describe digital pheromones as analogous, but better than the use of electrostatic potential fields to control movement. New information is quickly integrated into the field, while obsolete information is

automatically forgotten through pheromone evaporation. After developing simulations as proof of concept, Parunak et al. (2002) concluded that “swarming techniques inspired by insect pheromones offer a powerful mechanism for coordinating unmanned vehicles such as UAVs.”

Paul Gaudiano and colleagues at Icosystem Corp. are currently working under contract to DARPA to develop control strategies for robot swarms. Gerla and Yi (2004) from UCLA are sponsored by the Office of Naval Research (ONR) to investigate team multicast communications among autonomous sensor swarms. The Air Force Institute of Technology has developed a model of swarm-based, networked, sensor systems and espoused measures for the evaluation of swarm performance (Kadrovač and Lamont, 2002).

One aspect of swarm behavior, seen clearly in flocks of birds and schools of fish, is their ability to “see and avoid.” That is, they perceive and control their distance to their nearest neighbors and adjust altitude/depth and heading accordingly. How can this “swarming” emergent behavior contribute to UAV design? One fundamental aspect of “see and avoid” is to avoid one’s own teammates. This aspect of the swarming analog is entirely relevant to UAV applications. The other aspect of “see and avoid” in UAVs is to avoid terrain obstacles and all other aircraft in the National Air Space. It remains to be seen whether those issues may be informed by swarming emergent behavior.

Parunak, Brueckner, and Odell (2003) investigated three main approaches to swarming coordination:

- 1) relationship between individual agents and their group (“roles analysis”);
- 2) optimizing systems in light of constraints; and
- 3) processes inspired by natural systems (digital pheromones and biomimetics).

They investigated various instantiations of these approaches by creating software models.

Defence R&D Canada compiled a review of swarming UAVs from a control engineering perspective (Kim, Hubbard, and Necsulescu, 2003). The authors describe swarming

entities as autonomous units that can gather from different locations, act together, and then disperse. Swarming entities are decentralized, tolerant to variances of the units, or to addition/deletion of units.

Kim, et al. (2003) warn that the specificity of fixed-wing UAVs must not be ignored. They are not omnidirectional and cannot fly below a certain speed; therefore, group dynamics solutions must take into account the aerodynamic limitations of specific fixed-wing UAV flight envelopes.

Researchers and engineers are investigating alternative approaches to control trajectories of multiple UAVs, get sensors to the intended search locations, and avoid collisions. Vincent and Rubin (2004) from UCLA reviewed the concept of cooperating swarms and report on the design and analysis of cooperative search by simulated UAV swarms.

Sigurd and How (2003) reviewed local approaches to swarming based on nearest-neighbor interactions or potential fields. They summarize “flocking” approaches based on far-field attraction and a near-field repulsion between vehicles, but caution that perfect information about the location and dynamics of each vehicle is unlikely for a UAV swarm. Sigurd and How (2003) suggest the application of a “total field” approach using magnetic fields, and indicate that some biologists believe that similar mechanisms may be found in natural systems such as flocks of birds and schools of fish. Their results suggest that safe, but aggressive, navigation can be supported by this magnetic dipole approach without requiring each vehicle to know the position of any of the other vehicles.

The Navy program called “SWARM UAV” is only loosely related to the biomimetic concepts that inspired the acronym—Smart Warfighting Array of Reconfigurable Modules. This program was focused on the aeronautical development of a small, inexpensive UAV that could be used for a variety of purposes, including possible swarm applications (Castelli and Howe, 1999). This SUAV later became known as Silver Fox.

Figure 5 provides a schematic contrast of the control links and the associated workload or cognitive demand placed on a human controller for conventional control of multiple UAVs and for swarm control.

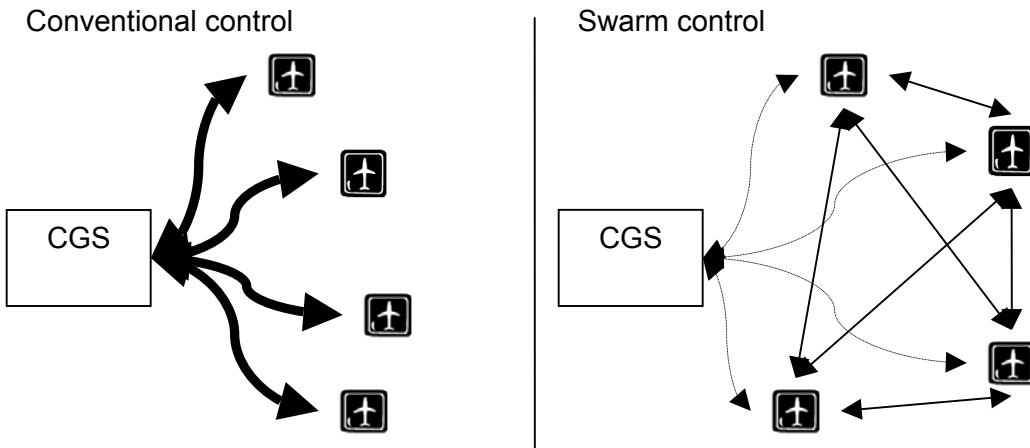


Figure 5. Control types of multiple UAVs (the thicker the communicating lines, the heavier the workload and cognitive demands on the CGS operators).

Entirely autonomous, emergent behavior is not a reasonable goal for military UAV systems. But, incorporating some aspects of effective swarm behavior in combination with top-level human control (see the “Playbook” example below) may prove to be an effective approach to achieving a favorable ratio of UAVs to humans and accomplishing ISR missions with minimal risk to humans.

Semiautonomy and the Human-Robot Interface

In semiautonomous systems, a human controller acts in concert with an intelligent system (semiautonomous agent). The level of autonomy may span a large range and it may be either constant or adjustable, varying with time, task difficulty, scenario segment, or the status/health/workload of the human. Designing the logical and the physical interfaces between the human(s) and the intelligent system is an important task. This interface is beginning to be known as the Human-Robot Interface (HRI).

According to Olsen and Wood (2004), HRI differs from traditional computer-human interface (CHI) design in two key ways:

- 1) robots operate in a physical world that is not completely under software control; and
- 2) the physical environment encountered by the robot imposes its own forces, timing and unexpected events that must be dealt with by the HRI system.

One common goal of HRI is to enable one human controller to control multiple robots. The number of robots that can be operated is called the “fan-out” of a human-robot team (Olsen and Wood, 2004). Goodrich, Olsen, Crandall, and Palmer (2001) offer the following classification for research on HRI:

- 1) autonomous robots;
- 2) teleoperation;
- 3) adjustable autonomy;
- 4) mixed initiatives; and
- 5) advanced interfaces.

Work on teleoperated systems is the most mature (Sheridan, 1992), but a difficult obstacle to effective teleoperation is the time delay in communications incurred as a function of the distance between the human operator and the robot. This is clearly an important issue for some UAV operations. In teleoperated systems, two approaches to this problem have been taken—the use of quickened or predictor displays and the application of automation features combined with supervisory control.

Research on the human role in supervising robots or semiautonomous systems has revealed both benefits and costs of various approaches and HRI designs. Systems that reduce human workload by participating in higher-level decision-making tasks are effective only if the automation is entirely reliable, which is a difficult undertaking (Parasuraman, Galster, and Miller, 2003). Consequently, the current view is that the best approach to HRI and to the interaction between humans and automated systems in general, is that the interface should be adjustable or adaptive. Humans should be able to delegate tasks as needed, and be provided with feedback information supporting supervisory control of those tasks. According to Parasuraman et al. (2003), this is equivalent to delegation as practiced in successful human teams.

The term “Optionally Piloted Vehicle” has been used to convey the concept of adjustable autonomy. The human controller has the option to take control of the vehicle, reverting from an autonomous or shared responsibility to a Remotely Piloted Vehicle, i.e., fully manual. The transition or transfer of control is the challenging part of the system design. Designing a control architecture and user interface that enables graceful transitions in

control in both directions—to and from human controller(s) to semiautomated agents—is an enormous challenge, but one that has substantial potential benefits for UAV operations.

Christopher Miller, in conjunction with Honeywell and SMA Information Flow Technologies, seems to have coined the term “Playbook” (Miller, Funk, Goldman, and Wu, 2004). Using the sports metaphor, Playbook represents a hierarchical system where the human, operating as the quarterback or coach, can “call the play” and the autonomous agents will execute their roles in the play. In mixed-initiative systems, presumably, one or more of the players could suggest plays to the decision-maker. The Playbook concept is consistent with earlier work on dynamic function allocation, also called “adaptive automation,” in which human and automated tasks can be allocated dynamically, depending on operator choice, workload, fitness, or similar variables (Kantowitz and Sorkin, 1987; Morrison and Gluckman, 1994).

MACBETH is a tactical planning software tool designed for applications in which a human user must quickly specify a mission to a team of autonomous agents. MACBETH combines hierarchical task network planning with constraint reasoning into a mixed-initiative planning system consistent with the “playbook” metaphor (Goldman, Haigh, Musliner, and Pelican, 2000).

The Playbook concept deserves further research and development. It provides an excellent conceptual architecture for human control of a multiple-UAV system.

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